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**A spatio-temporal analysis of trends in rainfall from long term
satellite rainfall products in the Sudano Sahelian zone of Nigeria**

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Abstract

Rainfall and its variability drive the rural economies across the Sudano-Sahelian zone of northern Nigeria, where drought strategies largely determine crop yields. The increasing scarcity of rain gauges in West Africa generally limits assessments of the degree and spatial extent of hardship arising from rainfall deficiency. However, the improved availability and robustness of satellite-based rainfall products since the early 1980s, offers an alternative source of rainfall data which is spatially, and often temporally, more complete than rain gauges. This research evaluates four satellite-based rainfall products for their ability to represent both long term rainfall trends such as recovery from decadal droughts, and trends in seasonal rainfall variables relevant to crop yield prediction. The Climate Hazards group Infrared Precipitation with Stations (CHIRPS) rainfall product at 5 km resolution, was observed to be consistently most representative of ground station rainfall across northern Nigeria over a 35-year period 1981 to 2015, followed by TARGAT. CHIRPS was found to give a good overall prediction of rainfall amounts at decadal, monthly and seasonal time scales, and was therefore used in the study to represent the typical performance of satellite rainfall datasets. The CHIRPS-observed increase in growing season length since the 1970s and 80s drought decades, was accompanied by significant rainfall increases in the later part of the growing season, especially marked in northern and northeastern states. This is especially important for the main subsistence crops sorghum and millet as the risk of late drought impedes swelling of the grain, affecting dry weight production. The CHIRPS data also indicate a significant decrease in dry spells in the northwest and southern parts of the study area, which would have favourable outcomes for crop production in the densely populated rural hinterlands of the cities of Sokoto, Jos and Abuja. In view of the continued intra-and inter-annual rainfall variability across northern Nigeria, and amid rapid rural population growth recently, a return to the rainfall levels of the

42 drought decades, would require informed response. The study suggests that satellite rainfall
43 estimates can offer such information, especially since we observed high spatial variability in
44 rainfall distributions and trends.

45 **Keyword:** Northern Nigeria, Rainfall recovery, Satellite rainfall products, Season rainfall
46 variables, Spatial-temporal analysis, Sudano-Sahelian.

1. Introduction

The Sudano-Sahelian ecological zone of Sub-Saharan Africa at Latitude (12°-20° N), is well known for its variable climate, where rainfall variability in the last three decades of the 20th century exceeded that in others parts of the world (Sanogo et al., 2015). The period 1931-1960 was considered to have above average rainfall, but an abrupt change occurred in the late 1960s, with up to 30% decline in average rainfall between 1961 and 1990 (Hulme, 1992; Fink et al., 2010). Severe droughts occurred during the 1970-1990 period (Nicholson, 2000), and those of 1972-1974 and 1983-1985 entailed severe food shortages, and loss of human life and livestock (Mortimore, 2000).

Northern Nigeria's climate is semi-arid, and rural livelihoods depend mainly on rain-fed agriculture (Hess et al., 1995; Tarhule and Woo, 1998), thus rainfall variability, which increases northwards, and changes in rainfall threaten the livelihoods of local people (Mortimore, 2000, Zhang et al., 2017). Timing of rainy season onset is important, as farmers make decisions about cropping and livestock movement which affect productivity, based on the first rains (Ingram et al., 2002). The major determinant of crop production is soil moisture, but the region's variable rainfall makes prediction of drought stress difficult. Drought stress during the seedling stage of the main cereal staples millet and sorghum results in reduced grain yield. For millet, drought just before the flowering period may reduce yields by up to 70% (Seetharama et al, 1984). Sorghum in particular is sensitive to late season rainfall, as sorghum does not enter the high water use period during its life cycle until August. Thus in addition to total seasonal rainfall and timing of rainy season onset, other important rainfall variables include the number, timing and length of dry spells, and seasonal distribution of rainfall is also an important variable.

69 There are many accounts of rainfall trends in northern Nigeria (Buba, 2010; Hess et al., 1995;
70 Olaniran, 1991, 1988; Mortimore, 2000; Tarhule and Woo, 1998; Tomlinson, 2010), mainly
71 observing severe declines in the last decades of the 20th century, followed by a return to normal
72 (Buba, 2010; Mortimore, 2000; Tomlinson, 2010). However, none provide a detailed study of the
73 last 2 decades for different rainfall variables specific to crop production and rural livelihoods. For
74 this, accurate rainfall data with high temporal, as well as spatial resolution is required.

75 Most of the rainfall in Africa is formed by convective clouds, thus rainfall amount can vary over
76 a few tens of km (Nicholson, 2000). However, the spatial distribution of rain gauge stations in
77 West Africa is very sparse and these were significantly reduced over the last 3-4 decades (Sanogo
78 et al, 2015). For example the number of gauges returning rainfall records in northern Kaduna state
79 (now Katsina state) diminished from about 50 in 1941-70 to only 12 by 1999 (Tomlinson, 2010).

80 Satellite based precipitation estimates provide an alternative to sparse, traditional gauge-based
81 rainfall measurements. They are at continental and global scale and have high spatial and -temporal
82 resolution. Thus they provide timely, repetitive and cost effective information about rainfall at
83 different time scales from daily to annual. It is therefore necessary to assess the accuracy of
84 different satellite based rainfall products compared to gauge rainfall, before they can be considered
85 operational for local crop production forecasting and rural productivity assessments. A few
86 previous studies have evaluated satellite-based rainfall products at continental scale: for West
87 Africa (Sanogo et al., 2015), and for three different river basins in Africa (Thiemig et al., 2012).

88 Also there are some studies at country level including Burkina Faso (Dembélé and Zwart, 2016),
89 Ethiopia (Bayissa et al., 2017) and Mozambique (Toté et al., 2015).

90 However, evaluations of satellite based rainfall products show large differences in algorithm
91 performance depending on location, local climate, season and topography (Maidment et al., 2013;

Tote et al, 2015). Also choice of the best rainfall product depends on the specific application. For drought monitoring studies, accuracy of low rainfall is the main requirement, and for hydrological and flood forecasting application, accuracy of high rainfall events is crucial (Toté et al., 2015).

Almost all studies of rainfall in northern Nigeria report great spatial variation in rainfall amounts and trends, with large differences in nearby areas, and many conflict with other studies (Buba, 2010; Mortimore, 2000; Tomlinson, 2010) for the same regions. Additionally, previous studies have been confined to data from a few climate stations, and are therefore spatially incomplete. In many cases satellite-based observations appear to conflict with farmers' perceptions of rainfall trends and its effects on their lives (West et al., 2008). This study aims to evaluate the available sources of both spatial and temporal rainfall data over recent decades in northern Nigeria, and to assess impacts on the rural landscape and agricultural economy.

The specific objectives of this study are: 1) to compare temporal trends in rainfall data from ground stations at daily, dekadal, monthly and annual time scales, with satellite-based estimates which use a combination of thermal infra-red and radar images, and ground station data, as satellite rainfall estimates can increase the spatial coverage if proved to be reliable; 2) to evaluate satellite rainfall products for retrieval of seasonal rainfall variables; 3) to analyse inter-annual variability and temporal trends over a 30-year period (1984-2013) from gauge-based rainfall variables; and 4) to analyse both spatial and temporal variability over the same 30-year period (1984-2013) using satellite derived rainfall variables.

2. Study area

The study area covers the Sudano-Sahelian savanna ecological zone of northern Nigeria between latitude 8°-16° N and longitude 1°-17° E. This zone covers the northern states and the Federal

114 Capital Territory Abuja (Figure 1). The landscape comprises rolling or gently undulating plains
115 often referred to as the “High Plains of Hausaland” (Mortimore, 1965).

116 Most rainfall in Nigeria comes from southwesterly winds from the tropical Atlantic Ocean, thus
117 the annual rainfall amount and duration of rainy season decreases from south to north, with greater
118 variability northward (Anyadike, 1993; Hess et al., 1995). The more southerly Sudan zone receives
119 more than 650 mm average annual rainfall falling to 400 mm in the Sahel zone. In the northern
120 states of Nigeria, over 80 % of the land is cultivated in the April to September rainy season. Over
121 the 35 years of this study, northern Nigeria has seen large increase in rural population densities.
122 (Tiffen, 2001; National Population Commission, 2006), accompanied by intensification of
123 agriculture. Kano’s rural population density was reported as 308 persons per km² in 2006 (National
124 Population Commission, 2006). However as nutritional status across northern Nigeria is low, with
125 20 to 50 % of children showing some degree of stunting and/or underweight (Hall and Bohen,
126 2009), return to the drought conditions of the 1970s and 80s, could be disastrous for farming
127 families.

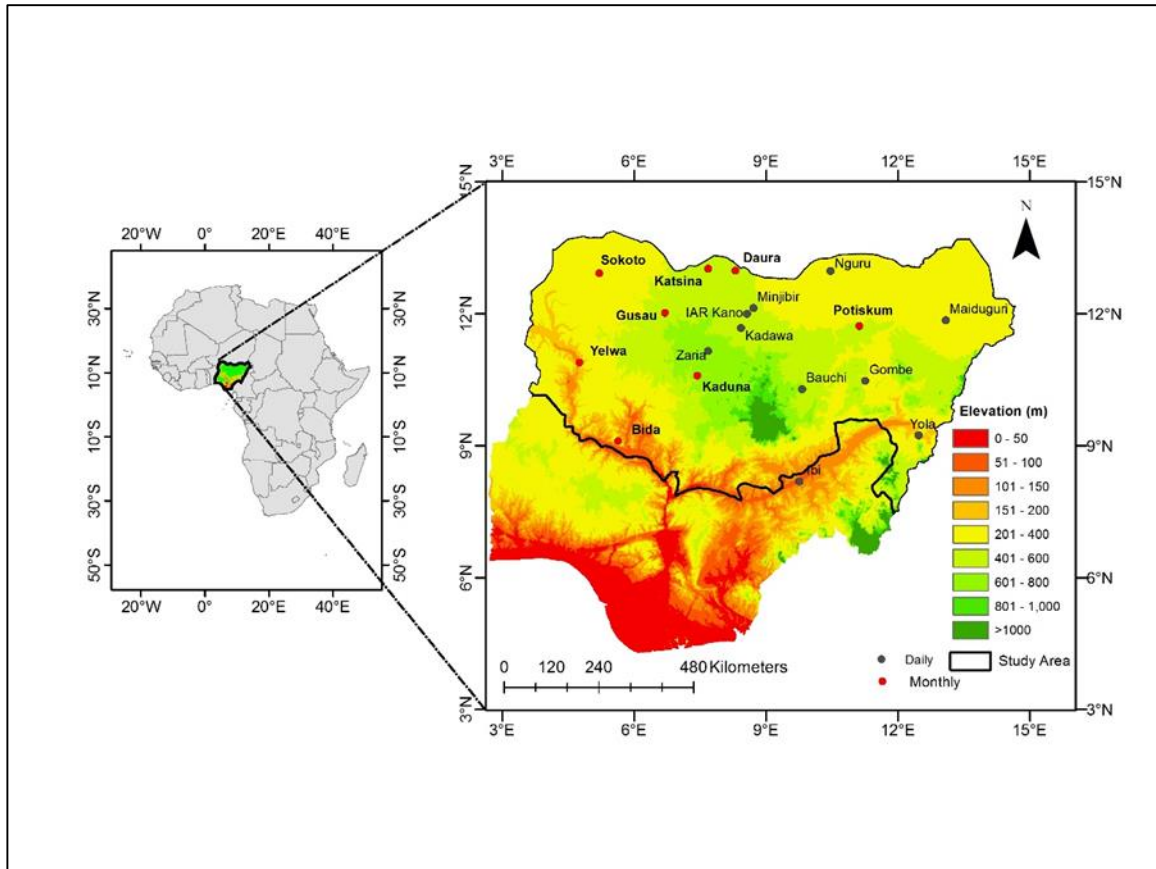


Figure 1. Location of northern Nigerian states and weather station rain gauges. Grey circles denote availability of daily and dekadal data, and red circles denote the location of available monthly data.

3. Datasets

3.1 In-situ gauge rainfall data

Daily rainfall data were obtained for 10 weather stations, including six (Bauchi, Gombe, Ibi, Nguru, Maiduguri, and Yola) from the Nigerian Meteorological Agency (NIMET) and four (Kadawa, Minjibir, IAR Kano, Zaria) from the Institute of Agricultural Research (IAR) (Figure 1 and Table 1). Only stations with above 80% data availability were considered for comparison with satellite based rainfall estimates. Daily rainfall data were accumulated to form dekadal (10 days), monthly and seasonal (Apr-Oct) rainfall for comparison with satellite based rainfall estimates.

Another 8 stations (Bida, Daura, Gusau, Kaduna, Katsina, Potiskum, Sokoto and Yelwa) having only monthly rainfall data were acquired from NIMET. However, the temporal coverage of weather stations varies from station to station.

3.2 Satellite based rainfall products

Satellite-based rainfall products typically exploit a combination of data from thermal infrared (TIR), passive microwave (PMW), and ground-based gauge observations, and these datatypes are often combined to create an optimal product. A variety of rainfall datasets has been produced using convective cloud top temperature by applying the cold cloud duration (CCD) technique (Maidment et al., 2014). In this study, four satellite-based rainfall products (Table 2), were selected for evaluation against rainfall gauge data, because of their long time series, near-real time data availability and free access.

Table 1. Overview of rain gauge stations.

No.	Weather station	Data availability	Temporal coverage	Latitude (° N)	Longitude (° E)	Elevation (m a.s.l)
1	Bauchi	Daily	1984-2013	10.27	9.82	584
2	Maiduguri	Daily	1984-2013	11.85	13.10	337
3	Nguru	Daily	1984-2013	12.96	10.46	343
4	Minjibir	Daily	1973-2015	12.12	8.70	429
5	IAR Kano	Daily	1998-2010	11.98	8.55	484
6	Kadawa	Daily	1984-2007	11.67	8.42	489
7	Zaria	Daily	1965-2015	11.14	7.67	660
8	Gombe	Daily	1984-2013	10.46	11.25	407
9	Yola	Daily	1984-2013	9.22	12.46	156
10	Ibi	Daily	1984-2013	8.17	9.74	107
11	Daura	Monthly	1951-2002	12.97	8.30	476
12	Bida	Monthly	1981-2015	9.10	5.63	190
13	Kaduna	Monthly	1981-2015	10.58	7.43	621
14	Katsina	Monthly	1981-2015	13.01	7.68	501
15	Sokoto	Monthly	1981-2015	12.91	5.20	307

16	Gusau	Monthly	1981-2015	12.01	6.70	508
17	Potiskum	Monthly	1981-2015	11.71	11.11	432
18	Yelwa	Monthly	1981-2015	10.88	4.75	160

TAMSAT African Rainfall Climatology and Time series (TARCAT)

The TARCAT v2.0, TIR based precipitation dataset at a spatial resolution of 4 km is based on the TAMSAT (Tropical Applications of Meteorology using Satellite and ground-based observations) rainfall estimation algorithm, which was constructed from archived Meteosat TIR imagery CCD, and locally calibrated against rain gauge records. It was developed by the University of Reading, UK, for Africa only, and is available from 1983 onwards at daily, dekadal, monthly and yearly scales (Maidment et al., 2014; Tarnavsky et al., 2014).

African Rainfall Climatology Version 2 (ARC2)

The ARC v2.0 (African Rainfall Climatology Version 2) satellite based daily gridded precipitation dataset centered over Africa at a spatial resolution of 10 km is also available from 1983 onwards, and uses inputs from three sources: 1) 3-hourly geostationary thermal infrared (TIR) data from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), 2) data from TRMM's microwave sensors and 3) quality controlled Global Telecommunication System (GTS) gauge observations reporting 24-h rainfall accumulations over Africa (Novella and Thiaw, 2013).

Tropical Rainfall Measuring Mission (TRMM)

The Tropical Rainfall Measuring Mission (TRMM) is a joint mission between the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency

(JAXA) aimed at improving observations of precipitation across the globe between 45° N and 45° S. The most widely used outputs are the TRMM Multi-satellite Precipitation Analysis (TMPA) 3-hourly (3B42) product accumulated to daily and monthly (3B43) products, which are available from 1998 to 2014 at spatial resolution of 25 km (Huffman et al., 2007; Maidment et al., 2014). The TMPA product depends on input from a combination of optical, thermal and microwave sensors, as well as gauge data (Dembélé and Zwart, 2016). Daily TRMM 3B42 V7 and monthly 3B43 V7 products were used in this study.

Climate Hazards group Infrared Precipitation with Stations (CHIRPS)

The CHIRPS Version 2.0 rainfall dataset was developed by US Geological Survey (USGS) and Climate Hazard Group at the University of California, Santa Barbara. It is available from 1981 onwards at spatial resolution of 5 km.

The CHIRPS algorithm i) incorporates satellite thermal IR data to represent sparsely gauged locations, ii) blends station data to produce a preliminary information product with a latency of about 2 days and a final product with an average latency of about 3 weeks, and iii) uses a novel blending procedure incorporating the spatial correlation structure of CCD-estimates to assign interpolation weights. CHIRPS also uses the TRMM's TMPA product, which includes several microwave sources, to calibrate global Cold Cloud Duration (CCD) rainfall estimates (Funk et al., 2015).

Table 2. Summary of satellite products used in this study.

No.	Satellite rainfall products	Temporal coverage	Data Input	Spatial Coverage	Spatial resolution	Temporal resolution
1	TARCAT Version 2.02	1983-2015	TIR, gauge	Africa	0.0375° (~4 km)	Daily
2	CHIRPS Version 2.01	1981-2015	TIR, gauge	Global	0.05° (~5 km)	Daily

3	ARC Version 2	1983-2015	TIR, gauge, TMPA 3B42 v7	Africa	0.1° (~10 km)	Daily
4	TRMM Multi-satellite Precipitation Analysis version 7 (TMPA 3B42 v7)	1998-2014	TIR, VIS, TMI, PR, gauge	Global	0.25° (~25 km)	Daily

4. Methods

4.1 Evaluation of satellite based rainfall products

Previous studies have found only weak relationships between satellites and gauge data for daily rainfall comparisons (Dembélé and Zwart, 2016; Sanogo et al., 2015). In this study we compare gauge rainfall against satellite data on daily, dekadal, monthly and seasonal time scales, for four different satellite-based rainfall products (ARC, CHIRPS, TAMSAT and TRMM). The period 1998 to 2014 was examined as TRMM data were only available for this period. Eighteen weather stations (Figure 1) were used, except for daily and dekadal (10 days) comparisons which were conducted for only ten weather stations which have daily rainfall data for this period (Table 1). Pixel values at gauge locations were extracted for comparison of gauge data with satellite rainfall estimates and accumulated into dekadal, monthly and seasonal values. For every month, the first two dekads comprise ten days, while the last dekad comprises 8-11 days depending on the month. Satellite rainfall estimates were compared with gauge rainfall using the pairwise comparison statistical measures, Pearson product-moment coefficient of correlation (R), Bias, Mean Error (ME) and Root Mean Square Error (RMSE).

Pearson correlation coefficient (R) measures the strength of linear relationship between satellite and gauge rainfall. Values of 'R' close to 1 indicate a perfect relationship between satellite and gauge rainfall estimates. The statistical significance of correlation (R) is represented by asterisks (** = $p < 0.01$ and * = $p < 0.05$)

$$R = \frac{\sum(G - \bar{G})(S - \bar{S})}{\sqrt{\sum(G - \bar{G})^2} \sqrt{\sum(S - \bar{S})^2}} \quad (1)$$

Where G = gauge rainfall amount, \bar{G} = average gauge rainfall amount, S = satellite rainfall estimates, \bar{S} = average satellite rainfall estimates, n = total number of data.

Bias indicates how well the average of satellite rainfall estimates corresponds with average of gauge rainfall. Values close to 1 show that cumulative satellite rainfall estimates are close to cumulative gauge rainfall measures. A Bias greater than 1 indicates satellite overestimates, while less than 1 indicate satellite underestimates.

$$\text{Bias} = \frac{\sum S}{\sum G} \quad (2)$$

Mean error (ME) is the measure of average difference between satellite and gauge rainfall amounts. A positive value reflects an overestimation of satellite rainfall whereas negative indicates underestimation of satellite rainfall.

$$\text{ME} = \frac{1}{n} \sum_{i=1}^n (S - G) \quad (3)$$

Root mean square error (RMSE) is the standard deviation of the difference between satellite rainfall estimates and gauge rainfall. A higher value of RMSE indicates large difference between satellite and gauge rainfall measures.

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (S - G)^2} \quad (4)$$

According to Toté et al (2015), for drought monitoring studies, overestimation of satellite rainfall ($\text{ME} > 0$) must be avoided and for hydrological and flood forecasting studies, underestimation of satellite rainfall estimate ($\text{ME} < 0$) should be avoided.

For analysis of changes in rainfall regime across northern Nigeria, seasonal rainfall variables were calculated from daily rainfall events. In this study, we used the definition of seasonal rainfall variables by Zhang et al (2017), as follows. Rainy season onset was defined as the first occurrence

of at least 20 mm cumulative rainfall within seven consecutive days after May 1, followed by at least 20 mm rainfall in the next 20 days to avoid “false starts”. Rainy season cessation was defined as the occurrence of less than 10 mm cumulative rainfall in 20 consecutive days after September 1. Length of rainy season was defined by the number of days between onset and cessation of rainy season. Season rainfall amount was defined by accumulating all daily rainfall events above 1 mm over the whole rainy season. Frequency of rainy season was defined by number of rainy days with rainfall amount ≥ 1 mm divided by the length of rainy season. Intensity of rainfall was defined as the total amount of rainfall during the rainy season divided by the number of rainy days with rainfall ≥ 1 mm. The number of rainy days was calculated according to different levels of rainfall amount with 1-10, 10-20, 20-30 and >30 mm/day separately. Seasonal distribution was defined by the ratio of amount of rainfall in the first and second halves of the rainy season (calculated based on onset and length of season). Dry spells within the rainy season were defined as rainfall below 1 mm in at least seven consecutive days. Dry spells were characterised by three variables, namely the number of dry spells, cumulative and mean length of dry spells by number of days. Ten weather stations with long term daily rainfall (Table 1) were used to derive these seasonal rainfall variables.

4.2 Temporal trend estimation from gauge based rainfall variables

To place satellite-based rainfall estimates in long term context, temporal trends in rainfall over northern Nigeria were calculated from gauge based rainfall variables for those stations which fall within Sanogo et al’s (2015) definition of the West African Sahel between latitudes 9° and 20° N, in terms of rainfall variability. To estimate the magnitude and direction of changes in seasonal rainfall variables, the Sen Slope method (Sen, 1968) was adopted. This is a linear regression model which calculates slope using the median value of slopes from all pairs of observations in a time

series (Equation 5), and thus is free from serial autocorrelation and heteroscedasticity, and is resistant to outliers and missing data within the time series. The significance of the observed trends was assessed by, the Mann–Kendall (MK) non-parametric significance test, which accounts for the effect of serial correlation (Salmi et al., 2002; Westra et al., 2013).

$$Q = \frac{Y_j - Y_i}{t_j - t_i} \quad (5)$$

Q is the slope.

Y_j and Y_i are values of time series, where j is greater than i,

There will be a total of N data pairs for which j is greater than i. The Sen Slope is the median of N values of Q.

4.3 Calculation of standardized anomalies for studying inter-annual variability

To study inter-annual variability over the long term, and due to strong spatial variability and uneven spatial distribution of rain gauges in Sudano-Sahelian region, we applied the Standardized Precipitation Index (SPI) (Ali and Label, 2009), to the rainfall variables using equation 2.

$$SPI = \frac{X_i - \bar{X}}{\sigma(X)} \quad (6)$$

Where X_i = regional rainfall variable for year i , where region refers average value of all rain gauge stations over the region of interest,

\bar{X} = average of the inter-annual regional rainfall variable,

$\sigma(X)$ = standard deviation of inter-annual regional rainfall variable.

4.4 Spatio- temporal trends for satellite rainfall variables

Since CHIRPS was observed to be the best overall satellite rainfall product when all variables were considered, CHIRPS was used to represent the spatio-temporal trends of rainfall variables across northern Nigeria. Trends from 1981 to 2015 were evaluated for every pixel in the study area, using Sen slope, and the Mann–Kendall (MK) significance test.

5. Results and discussion

5.1 Evaluation of satellite rainfall estimates

In this study four satellite-based rainfall products were evaluated against gauge data from the 10 weather stations having daily data (Figure 1), to identify the best rainfall product for northern Nigeria at daily, dekadal, monthly and seasonal time scales. Also satellite rainfall products were evaluated for different rainy season variables to find the best product for analyzing temporal trends in rainy season characteristics over space. For all the plots (Figures 2-7), the red line is the 1:1 line, the solid blue is linear regression line between gauge and satellite estimates and the dashed blue lines are 95 % confidence intervals (CI).

5.1.1 Daily comparison

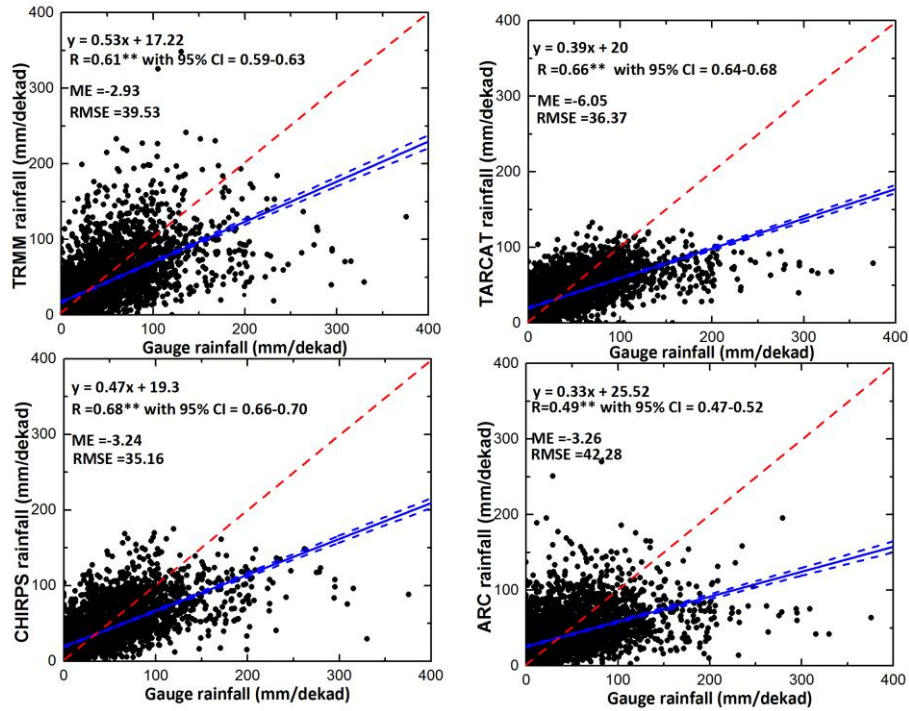
Comparison between satellite-based daily rainfall estimates from ARC, CHIRPS, TARCAT and TRMM and individual rain gauge stations for the period 1998-2014 shows only weak relationships, with correlation coefficient 'R' values ranging from 0.3 to 0.5. The best overall performance was observed for TARCAT ($R = 0.45$), followed by CHIRPS ($R = 0.35$), ARC ($R = 0.34$) and TRMM ($R = 0.32$), although TARCAT showed the greatest Bias (0.90). All of the satellite products show substantial overestimation of low rainfall events and underestimation of high rainfall events. This accords with other studies in northern Nigeria (Sanogo et al, 2015) and Burkina Faso (Dembélé and Zwart, 2016).

5.1.2 Dekadal comparison

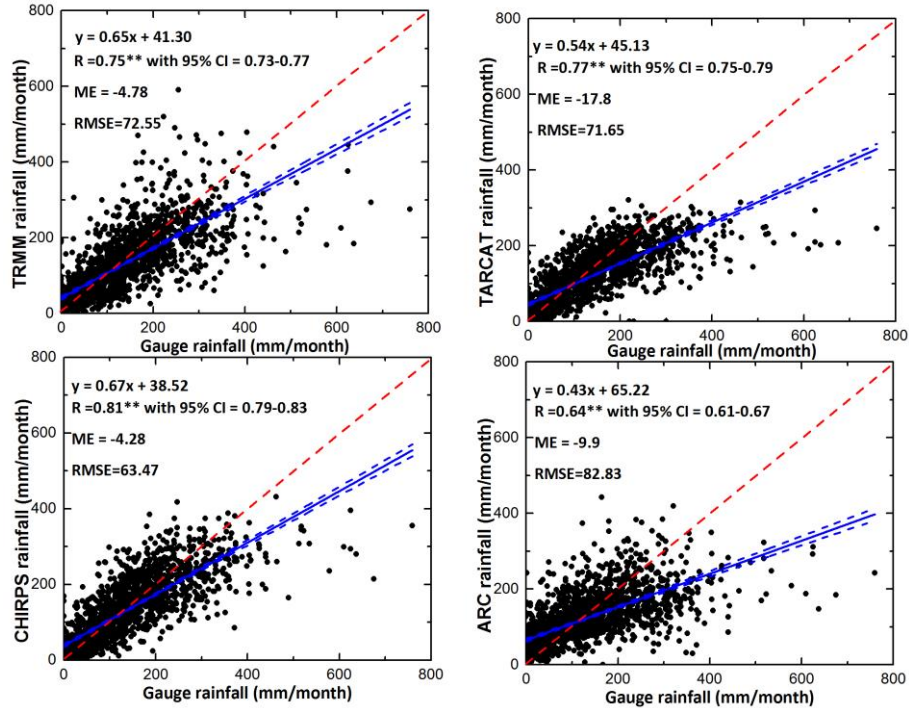
Dekadal (10 days) comparisons (Figure 2) show a good agreement between gauge rainfall, and CHIRPS and TARCAT satellite estimates respectively, with correlation coefficient ‘R’ values between 0.50 and 0.80 for the majority of weather stations. Correlation values for TRMM (0.49-0.73) and ARC (0.24-0.69) were somewhat lower. CHIRPS was also found to have the best Bias close to one (0.79-1.10), followed by ARC (0.74-1.12), TARCAT (0.60-1.17) and TRMM (0.73-1.21). The lowest RMSE values were found for CHIRPS (35.16 mm.dekad⁻¹), followed by TARCAT (36.37 mm.dekad⁻¹), TRMM (39.53 mm.dekad⁻¹) and ARC (42.28 mm.dekad⁻¹). The superior overall performance of CHIRPS for dekadal rainfall was also noted for Ethiopia (Bayissa et al, 2017) and Mozambique (Toté et al, 2015). All satellite products show overestimation of low, and underestimation of high dekadal rainfall amounts, for the majority of weather stations. In terms of agricultural yield prediction, such underestimation of dekadal rainfall by satellite products is not as critical as overestimation, as the major stress on the main cereals crops sorghum and millet is drought especially 15 to 20 days of no rain in mid-growing season (Seetharama et al, 1984).

5.1.3 Monthly comparison

Monthly satellite estimates show better performance than at daily or dekadal scales, with correlation values between 0.55-0.86 for all satellite products except for ARC (Figure 3).



316 Figure 2. Comparison of dekadal (10 days) rainfall, between rain gauge and satellite rainfall
 317 estimates for 10 weather stations for 1998-2014.



318 Figure 3. Comparison of monthly rainfall between rain gauge and satellite rainfall estimates for
 319 18 weather stations for 1998-2014.

This improvement is because aggregation of daily or dekadal data into monthly values cancels out errors at daily or dekadal scales (Dembélé and Zwart, 2016). The monthly satellite estimates for all 18 weather stations for the period 1998-2014 in mm/month, compare well with gauge rainfall. Overall CHIRPS gives the best results with the highest correlation value of 0.81 and lowest RMSE value of 63.47 mm/month, and for CHIRPS, the blue trend line is closest to the red 1:1 line. Lower correlation values were observed for TARCAT, TRMM and ARC of 0.77, 0.75 and 0.64 respectively. These findings are in agreement with Bayissa et al (2017) in Ethiopia and Toté et al (2015) in Mozambique, who reported that CHIRPS performed better than other satellite estimates at monthly scale.

5.1.4 Yearly comparison

Monthly rainfall data from April to October were accumulated for both satellites and gauges, to produce seasonal (yearly) rainfall totals, for the 16 years, 1998 to 2014 for the 18 weather stations. A good agreement was observed between satellite and gauge rainfall data with correlation values ranging between 0.62-0.79 (Table 3). Highest correlation values were observed for CHIRPS (0.79) and lowest for ARC (0.62), and a Bias close to 1 was found both for CHIRPS and TRMM (0.97), followed by ARC (0.93) and TARCAT (0.84) respectively. The observed negative values of ME (Table 3) indicate that all satellite datasets underestimate seasonal rainfall compared to gauge measurements. The lowest value of mean error was observed for CHIRPS (-27.38 mm/season) followed by TRMM (-29.7 mm/season), ARC (-58.7 mm/season) and TARCAT (-141.3 mm/season) respectively. Similarly the lowest value of RMSE was found for CHIRPS (196.6 mm/season), followed by TRMM (214.3mm/season), ARC (264.4 mm/season) and TARCAT (274.3 mm/season) respectively. These findings accord with those of Bayissa et al (2017), who observed best correspondence of CHIRPS with gauge data at seasonal time scale in Ethiopia, but

disagree with Dembélé and Zwarts (2016), whose seasonal satellite data indicate overestimation of annual rainfall in Burkina Faso, as our data indicate underestimation.

Table 3. Yearly comparison of satellite rainfall products.

	TRMM	TARCAT	CHIRPS	ARC
Correlation (R)	0.75**	0.69**	0.7**9	0.62**
Bias (no units)	0.97	0.84	0.97	0.93
Mean Error (mm/season)	-29.7	-141.3	-27.3	-58.7
RMSE (mm/season)	214.3	273.9	196.6	264.4

** Statistically significant at 0.01 level.

5.1.5 Seasonal rainfall variables

A spatial correlation between three satellite datasets (TARCAT, CHIRPS and ARC) and gauge based rainfall variables for 10 weather stations was undertaken for the period 1984-2013. TRMM data are not included as they are not available for the earlier years 1984-1997, and we observed the TRMM data quality to be consistently inferior to CHIRPS and TARCAT. For the onset and cessation of rainy season, satellite estimates compare fairly well with the gauge-based data, with correlation coefficient R values between 0.53 and 0.65 for onset, and 0.59 and 0.70 for cessation, with ARC showing the lowest values (Figure 4). Similarly for length of season and amount of rainfall, a linear relationship between satellite and gauge based rainfall measures is observed with R values between 0.63 and 0.74 for season length, and 0.57 and 0.78 for rainfall amount. Again ARC indicates lower values of R (0.63, 0.57) for length and seasonal amount of rainfall compared to CHIRPS (0.71 and 0.78) and TARCAT (0.74 and 0.61) (Figure 5 scatterplots). For the total number of rainy days per season, a high value of R = 0.79 was observed for CHIRPS compared to ARC (0.74) and TARCAT (0.72) (Figure 6a-c). Thus in summary, for onset, cessation and length

of season, although CHIRPS showed the best overall performance, if confidence intervals (blue dashed lines on Figures 4 a-f and 5 a-c) are considered, TARGAT should be deemed equally robust. However, a marked discrepancy existed between satellite and station data, for rainy days with given stepped intervals of rainfall (Figure 6d-o). For rainy days with low rainfall amounts of 1-10 and 10-20 mm/day, a higher number of rainy days were observed for satellite products compared to gauge measurements (Figure 6d-i), and this is in agreement with Zhang et al (2017) who also report a higher number of small rainfall events estimated by satellite compared to gauge data. On the contrary, satellites observe a lower frequency of high rainfall events > 30 mm/day, than ground stations (Figure 6 m-o), and this is in line with the findings of Toté et al (2015), who reported large underestimation of high rainfall events by the satellite product. In this study, CHIRPS outperformed ARC and TARGAT for all stepped intervals of rainfall events (Figure 6 a-o) except for the lowest class 1-10mm/day (Figure 6d-f), when TARGAT obtained the lowest error.

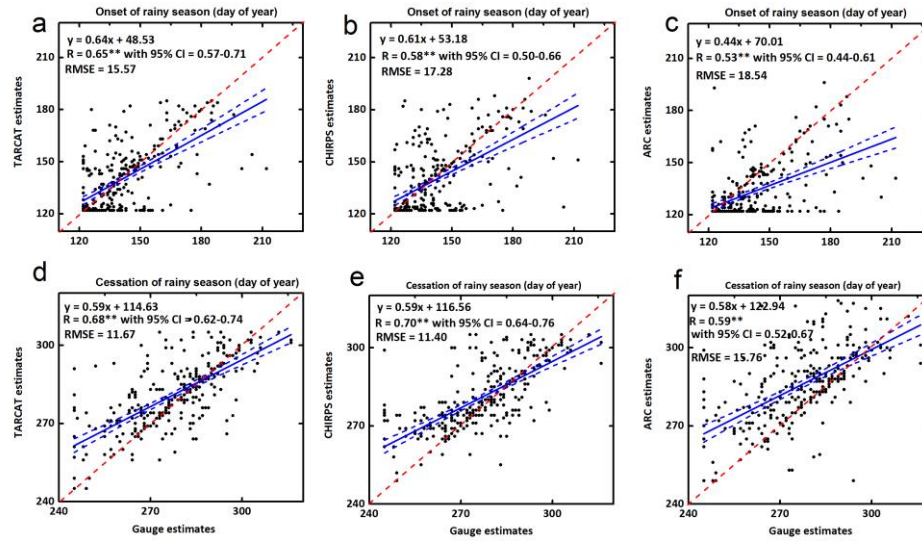


Figure 4. Comparison between gauge and satellite, for onset of rainy season (day of year) (a-c) and cessation of rainy season (day of year) (d-f) for all weather stations (1984-2013).

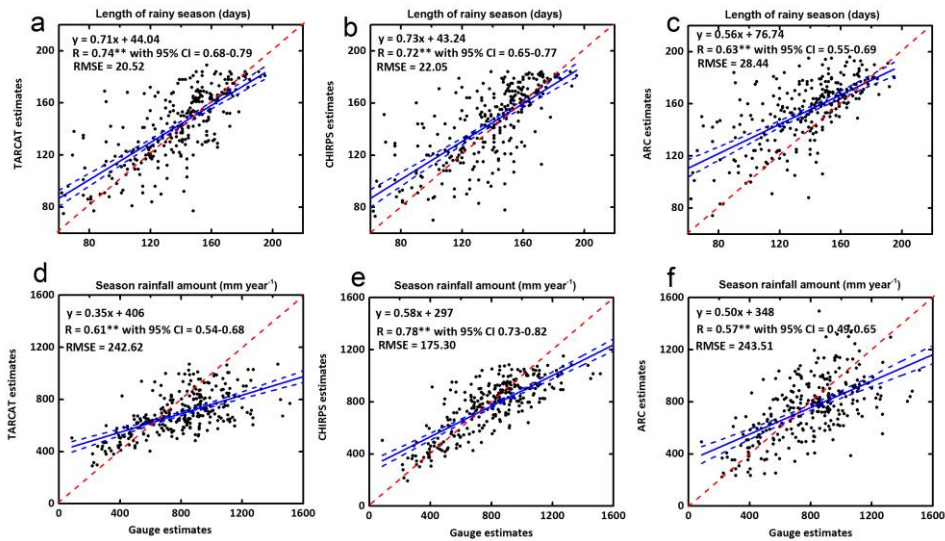


Figure 5. Comparison between gauge and satellite, for length of rainy season (days) (a-c) and seasonal rainfall amount (mm year⁻¹) (d-f) for all weather stations (1984-2013).

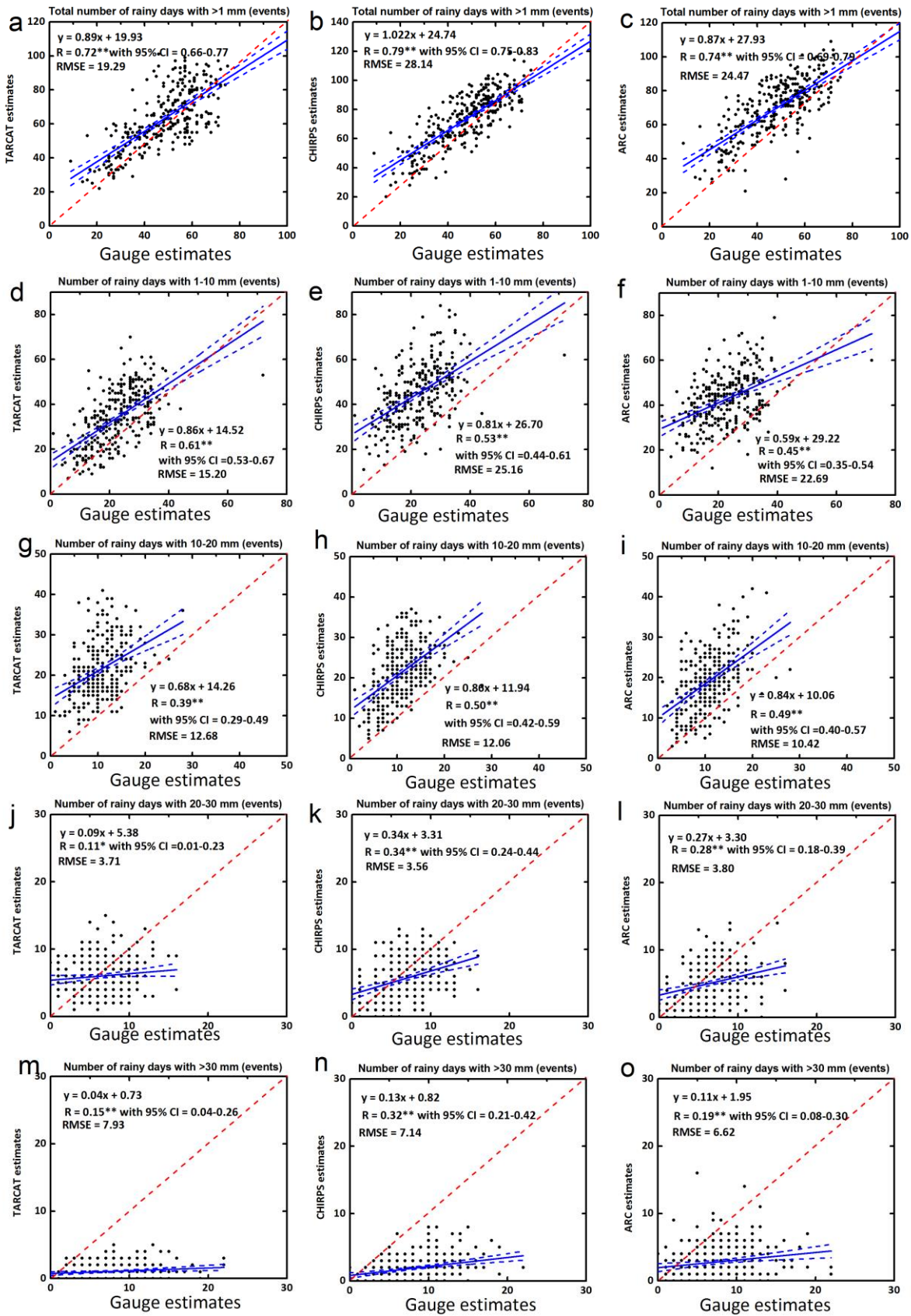


Figure 6. Comparison between gauge and satellite, for the total number of rainy days with >1 mm day⁻¹ (a-c), with 1-10 mm day⁻¹ (d-f), with 10-20 mm day⁻¹ (g-i), with 20-30 mm day⁻¹ (j-l) and with >30 mm day⁻¹ (m-o) rainfall amount for all weather stations (1984-2013).

The higher number of low rainfall events captured by satellite products affects the estimation of dry spell variables, with a lower representation of dry spells. Thus we observe a very weak correlation for number of dry spells (0.02-0.09), mean length of dry spells (0.03-0.13) and cumulative length of dry spells (-0.005-0.03) for all three satellite datasets. Toté et al (2015) also found a large error in the detection of dry spells, with RFE data (only available since 2001) showing the best performance compared to CHIRPS and TARCAT.

Due to this high representation of low rainfall events by satellite products, a higher total number of rainy days (Figure 6a-c) and higher frequency of rainfall (Figure 7 a-c) are observed for satellite products. Correspondingly a lower representation of intensity (Figure 7 d-f) of rainfall events for satellite products is observed, as Intensity is the ratio between seasonal rainfall amount and total number of rainy days per season.

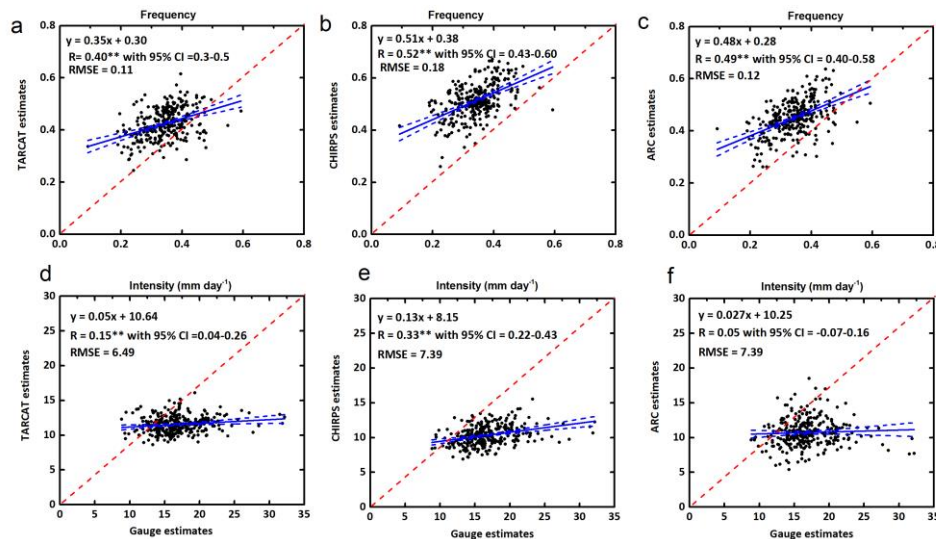


Figure 7. Comparison between gauge and satellite, for frequency (a-c) and intensity of rainy season (d-f) for all weather stations (1984-2013).

The satellite rainfall variables best representing gauge data were total annual (seasonal) rainfall, the total number of rainy days, and length of rainy season. These good results for variables measured across the whole rainy season, may be partly due to positive and negative errors cancelling out. The overestimation of rainy days by satellites is due to detection of low and patchy rain within a pixel, compared to a ground point where no rain has fallen. However, this is a serious shortcoming of satellite estimates, as this could suggest adequate rainfall during a drought.

Notwithstanding, although rainfall variables based on single-day rainfall events may show bias due to difference in scale between point-based gauge and large area satellite data, the temporal trends in rainfall variables from satellite data are still expected to be valid.

5.2 Temporal trends for northern Nigeria using gauge based rainfall variables

Temporal trends over northern Nigeria were estimated over three decades, from 1984 to 2013 using the average value for every year of nine stations (excluding Ibi weather station lying in Guinea zone) having daily data (Figure 1). Clear significant and positive trends were observed for the seasonal rainfall amount, cessation and length, as well as for rainfall intensity, the total number of rainy days and rainy days with more than 30 mm rainfall (Table 4). Our findings support those of Sanogo et al (2015), who observed similar trends from 1980 to 2010, using all gauges averaged over the West African Sahel region (Latitude 9°-20° N).

Table 4. Trends from 1984 to 2013 for gauge based rainfall variables (averages over all stations) were estimated using Sen's slope (with slope expressing changes in units per year). Positive (negative) values indicate increasing (decreasing) rainfall variable trends and statistically significant changes are denoted by asterisks ($+p \leq 0.1$, $* = p \leq 0.05$; $** = p \leq 0.01$; $*** = p \leq 0.001$) with respect to the Mann-Kendall test accounting for temporal autocorrelation.

	Season rainfall variables	Gauge- trends
1	Onset of Rainy Season (day of year)	-0.18
2	Cessation of Rainy Season (day of year)	0.44*
3	Length of Rainy Season (days)	0.53*
4	Season rainfall amount (mm year ⁻¹)	8.2**
5	Frequency	0
6	Intensity (mm day ⁻¹)	0.12**
7	Number of rainy days with 1-10 mm (days)	0
8	Number of rainy days with 10-20 mm (days)	0.02
9	Number of rainy days with 20-30 mm (days)	0.02
10	Number of rainy days > 30 mm (days)	0.11**
11	Season distribution	-0.001
12	Total number of rainy days with > 1mm (days)	0.18+
13	Cumulative dry days (days)	0.21
14	Length of Dry Spell (days event ⁻¹)	0.03
15	Number of Dry Spells (events year ⁻¹)	0.002

The rainy season starting date, which is critical for farming, showed non-significant trends (Table 4), which is in agreement with Sanogo et al's (2015) gauge-based observations in the Sahel. We also observed significant positive trends for number of days of heavy rainfall over 30 mm, and in consecutive wet days, but insignificant trends for dry spells (Table 4) which accords with Sanogo et al's (2015) observations for the Sahel. This suggests that recovery of rainfall in northern Nigeria since the drought decades of 1970s and 80s is mainly related to increase in number of rainy days

(Table 5), a higher number of extreme rainfall events and later cessation of rainy season, rather than earlier onset of rains, or a reduction in the length or number of dry spells.

On the other hand, while Hess et al's (1995) study of northern Nigeria during the drought decades of 1970s and 80s had similar findings of no changes in rainy season onset even during the drought decades, they did observe a dramatic fall in the average number of rainy days per rainy season during those dry decades (Hess et al, 1995).

Table 5. Average number of rainy days per year for five different decades for three northerly station bordering the Sahel zone.

	1951- 1960	1961- 1970	1971- 1980	1981- 1990	1991- 2000	2001- 2010
Maiduguri		47	35	30	42	41
Nguru		36	27	20	29	27
Daura	46.7	42.4	37	29.9	35.5	

5.3 Spatial distribution of monthly and annual rainfall trends using gauge data (1984-2013) and CHIRPS rainfall product (1981-2015)

Monthly rainfall data are required to investigate trends in total annual rainfall as well as its seasonal distribution. Thus the spatial aspects of trends in monthly and total annual rainfall between 1984 and 2013 were investigated based on both rain gauge data and CHIRPS data for the period 1981-2015 (Table 6 and Figure 8), as CHIRPS proved to be the most robust satellite rainfall product, and can be used to represent the typical performance of satellite rainfall datasets. CHIRPS satellite data for the 35-year period 1981 to 2015, show clear positive trends in annual rainfall over most of northern Nigeria (Figure 10). The CHIRPS observations are supported by clear positive trends in annual rainfall evident at stations across northern Nigeria (Table 6), which confirms rainfall recovery after the droughts of the 1980s.

455

456 Table 6. Trends for gauge based total annual and monthly rainfall using Sen's slope for the
 457 period 1981-2015. Statistically significant changes are denoted by asterisks (+= $p \leq 0.1$, * = $p \leq$
 458 0.05; ** = $p \leq 0.01$; *** = $p \leq 0.001$) with respect to the Mann-Kendall test accounting for
 459 temporal autocorrelation.

Station	Total Annual	April	May	June	July	August	September	October
Sokoto	5.6*	0	0.9	0.2	0.2	2.1*	0.9	0.3**
Nguru	4.4 ⁺	0	0.3	1.1 ⁺	-0.02	1.9	1.23	0.2*
Gusau	2.6	0	0.4	-0.2	0.7	1.1	-1.6	0.9*
Katsina	7.5**	0	0.3	0.9	-0.06	4.3**	0.4	0.3**
Minjibir	8.1 ⁺	0	-0.06	1.0	2.5*	3.2	1.7 ⁺	0.4*
Kano	11.2**	0	0.3	2.7*	3.1*	3.9	1.6	0.07
Maiduguri	10.2***	0	0.2	1.8	2.6	3.2	2.1	0.6
Kadawa	6	0	-0.2	-0.8	-0.3	4.8 ⁺	1.4	1.2
Potiskum	4.2	0	0.2	1.7*	1.3*	0.6	2.7*	0.1
Zaria	9.9***	0.3	0.9	-0.07	0.7	2.9	4.6**	1.4 ⁺
Yelwa	4.1	0.3	0.4	-0.002	-0.4	3.6	2.5*	0.6
Kaduna	1.7	0.07	-0.08	-0.4	0	-0.9	1.7	2.1*
Bauchi	21.4***	0.3	-0.8	3.3*	3.7	6.2*	2.3	0.8
Yola	-5.7	-0.9	-1.3 ⁺	2.2 ⁺	-3.2**	-1.3	1.1	0.9
Ibi	-1.2	0.1	-1.4	-0.1	-0.5	-3.2*	0.9	0.9

460

461 Our satellite and gauge-based results conflict with Sanogo et al (2015) ARC-based estimates of
 462 rainfall trends for northern Nigeria, as they report negative but insignificant trends for seasonal
 463 rainfall amount for areas surrounding our climate stations of Kaduna, Zaria, Kano, Minjibir and
 464 Gusau. They suggest that decline in the number of GTS ground stations for these areas explained
 465 the observed negative trends using ARC-based satellite data. The reliance of CHIRPS on high
 466 resolution climatology (Toté et al., 2015) and multiple satellite products including visible, thermal
 467 infra-red and microwave as opposed to ARC's emphasis on ground station data may explain the
 468 better result for long-term rainfall trends from CHIRPS.

Our CHIRPS satellite data observe a trend of increased rainy season length (Figure 9), with more rain in the months of August to October (Figure 8), and this is supported by our ground stations (Table 7). Our gauge observations indicate that the observed increase in annual rainfall is due to increases of 1-2 mm/year in each of the months August to October (Table 7) and these months contribute over 50% of annual rainfall amount.

Table 7. Trends for gauge based monthly rainfall (average for all gauges in northern Nigeria) for the period 1984-2013.

Months	March	April	May	June	July	August	September	October
Trend Slope	-0.08**	-0.06	-0.07	0.74**	0.78	2.22**	1.40 ⁺	1.05**
Contribution to annual rainfall (%)	0.37	2.28	7.90	13.46	23.36	30.25	18.24	4.10

In August, the month with greatest overall increase in rainfall, distribution of the increase is extremely patchy, with large increases of over 4 mm in the northeast, but non-significant trends in many other areas. A marked decrease in September around the Federal Capital Territory in the south, is also evident. Thus CHIRPS satellite products give a better spatial representation of overall long term rainfall trends, growing season length, and distribution of rainfall within the growing season, than ground station data.

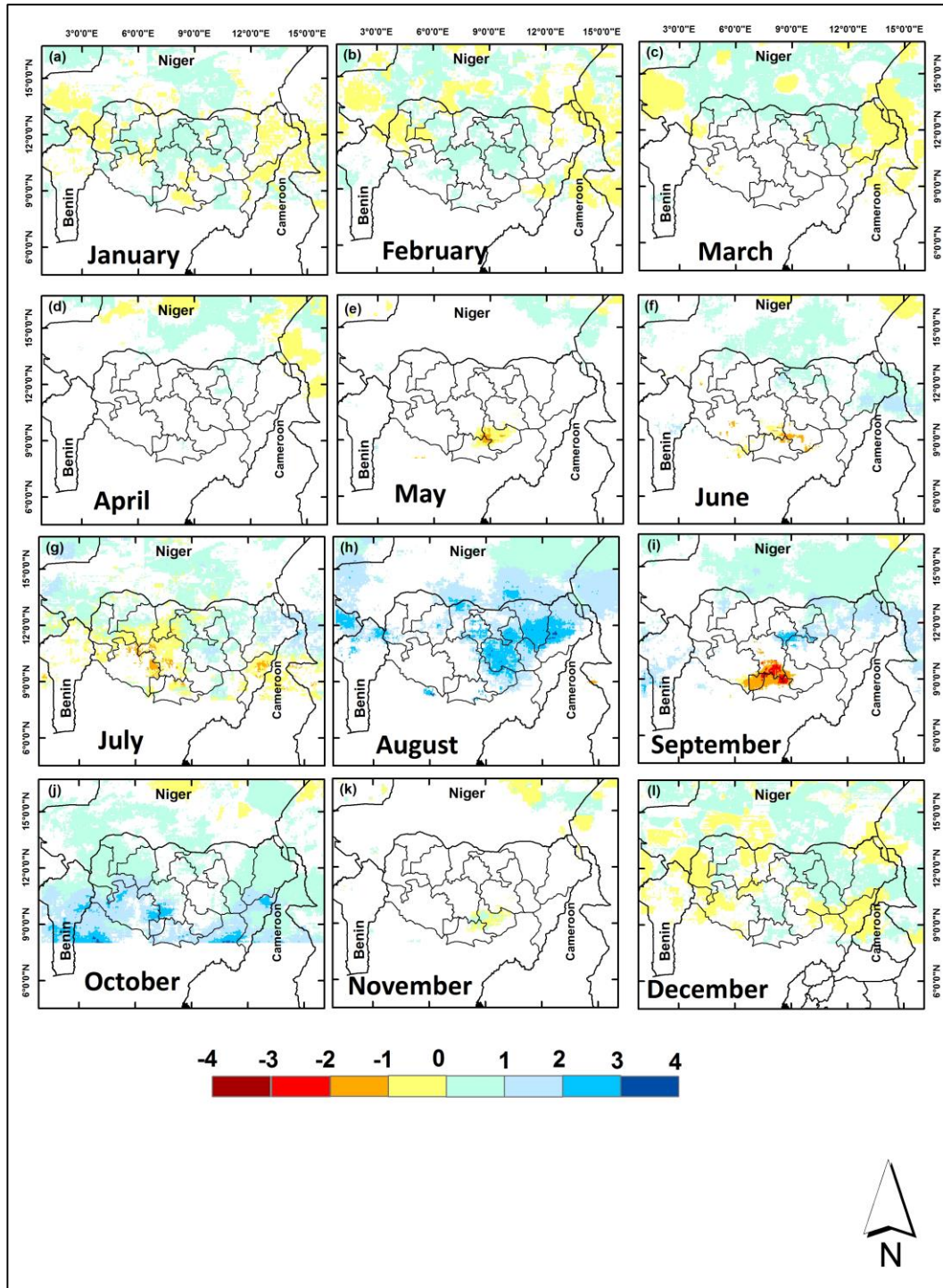


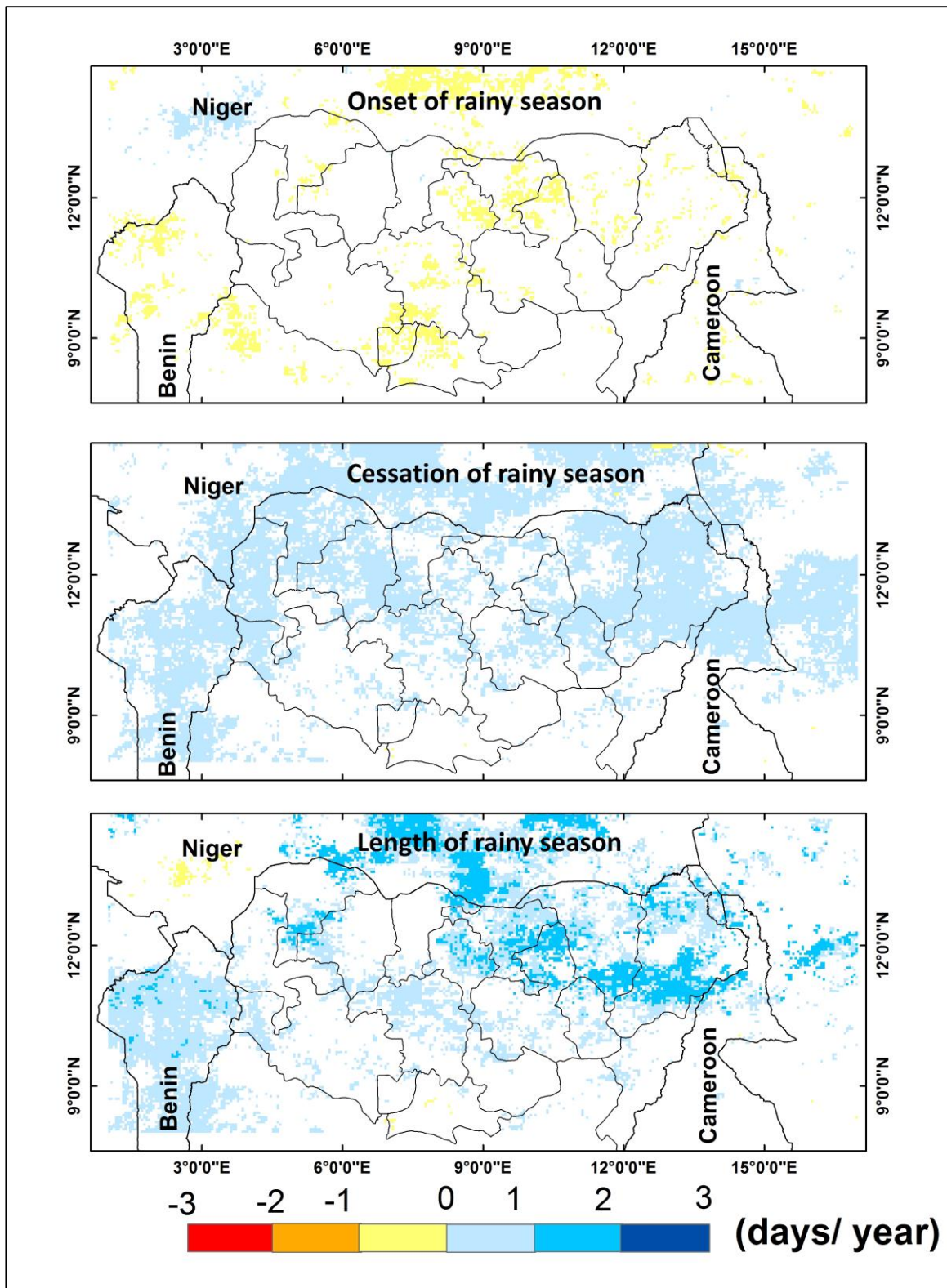
Figure 8. Spatial temporal trends in CHIRPS based monthly rainfall between 1981 to 2015 based on Sen's slope expressing change in monthly rainfall in mm/year. White areas showing non-significant trends at 90% confidence level with respect to the Mann–Kendall test.

5.4 Spatio-temporal trends in CHIRPS rainfall variables (1981-2015)

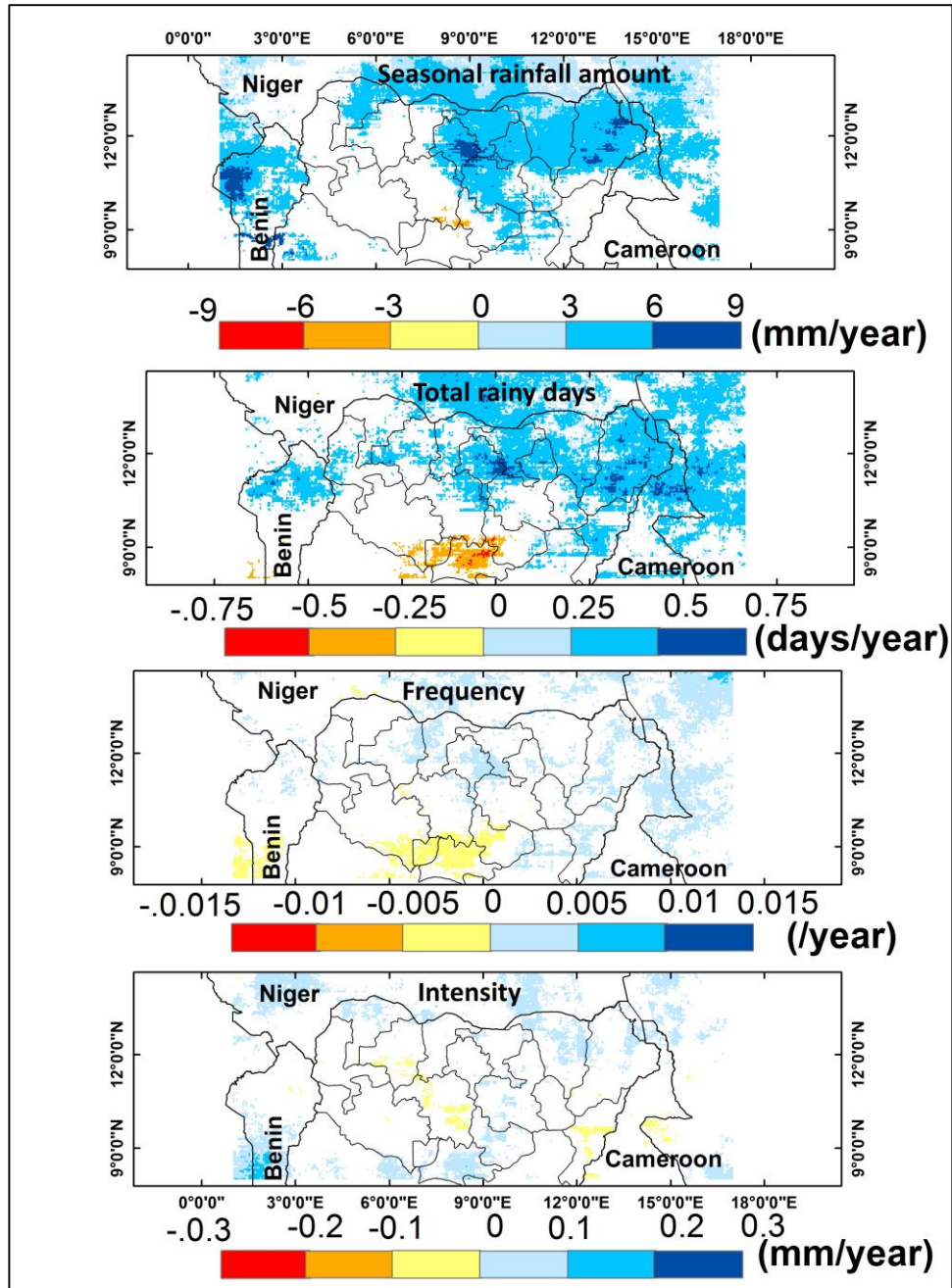
CHIRPS satellite-based observations indicate significant positive changes between 1981 and 2015 for seasonal rainfall amount, which represents the traditional May to September growing season, and these increases are most marked in northeastern and north central Nigeria (Figure 10) around the cities of Maiduguri and Kano, with dense rural populations dependent on agriculture. A significant but less marked increase in seasonal rainfall is also evident in the extreme northwest of Nigeria around the city of Sokoto, also with a densely settled rural hinterland. Significant positive changes across the whole region are also observed for total annual rainfall amount and the total number of rainy days (Figure 10). However, the distributions are extremely patchy, with some areas gaining over 9 mm annual rainfall, adjacent to areas with no gain.

The length of rainy season also showed significant positive trends over most of northern Nigeria (Figure 9), indicating that the rainy season has become longer in recent years, due to a late ending. The onset of rainy season shows non-significant trends in most parts of northern Nigeria, so indicating little change in the start of the rainy season, thus the longer rainy season appears mainly due to later cessation of rains.

The number, cumulative length and average length of dry spells (Figure 11) show a decreasing trend over the whole area but especially in northwestern Nigeria. This would have favourable implications for crop production and crop security, as a non-interrupted supply of moisture throughout the growing season is essential for a good yield.

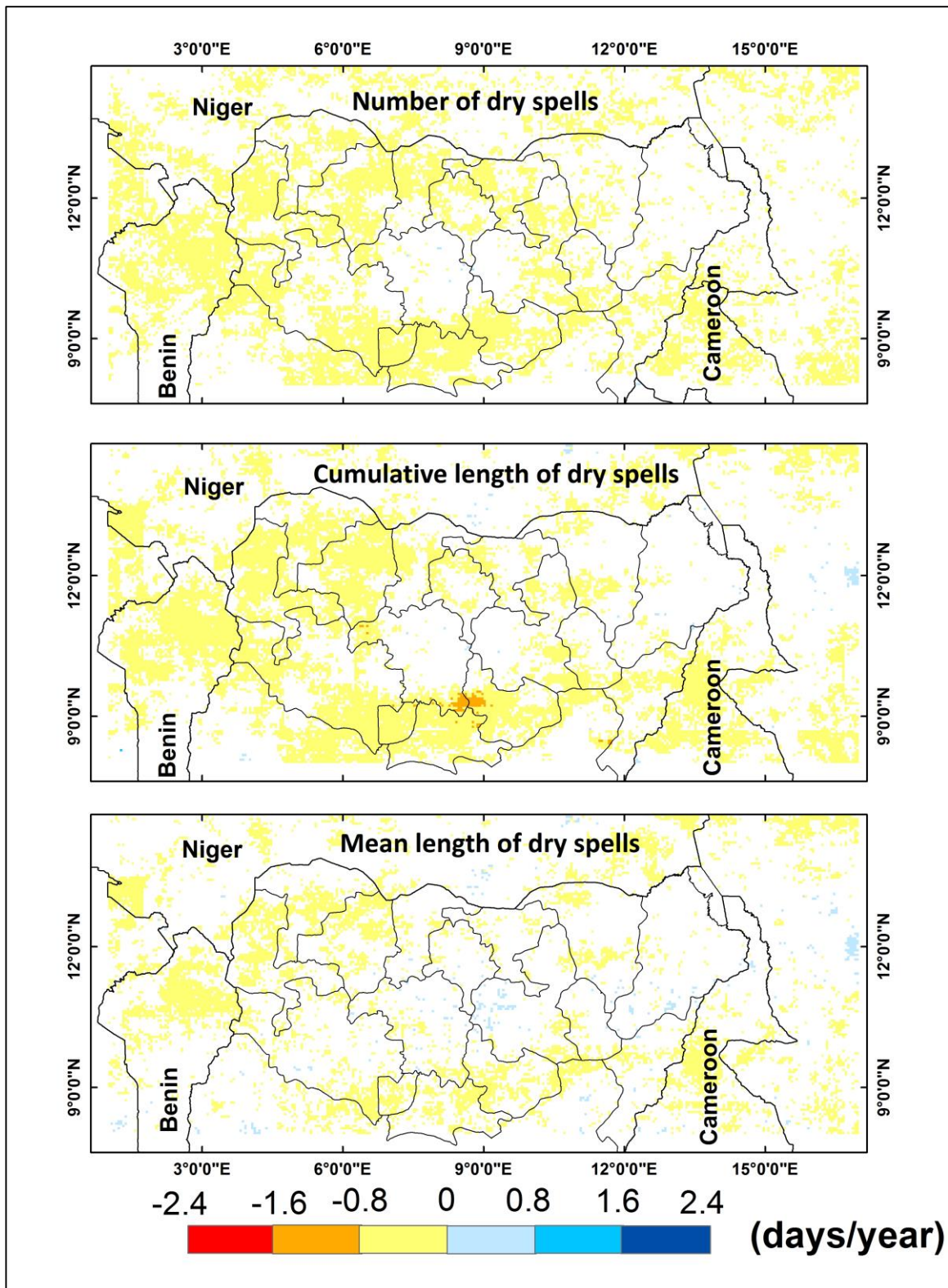


508 Figure 9. Spatial temporal trends for seasonal onset (day of year), cessation (day of year) and
509 length (days) using CHIRPS data between 1981 and 2015 based on Sen's slope expressing changes
510 in days/year.



511

512 Figure 10. Spatial temporal trends for seasonal rainfall amount (mm/year), total number of rainy
 513 days per season (days), frequency (no units) and intensity (mm/day).



514 Figure 11. Spatial temporal trends for total number (events /year), cumulative length (days/year)
 515 and mean length of dry spells (days/event) using CHIRPS data between 1981 and 2015 based on
 516 Sen's slope.

5.5 Discussion

Of the four satellite rainfall products examined, CHIRPS demonstrated the best results with consistently higher correlation for most variables, a Bias closest to 1 and lower error, when compared to ground station data. The results for TARGAT were also consistently good, with confidence intervals overlapping with those of CHIRPS. The robustness of satellite rainfall estimates increased with increasing aggregations of daily data, due to cancelling out of positive and negative errors. Thus for dekadal (monthly) data, CHIRPS, with r of 0.68 (0.81) and Bias close to 1, of 0.95 (0.98) observed good results. The observed underestimation of dekadal rainfall by all four satellite products, with $ME < 1$, is not as critical for agricultural yield prediction as overestimation, as the major stress on the main cereal crops of northern Nigeria, sorghum and millet is drought, especially 15 to 20 days of no rain in mid-growing season. For drought monitoring, overestimation of satellite rainfall ($ME > 1$) should be avoided, as it would tend to overlook drought periods.

All satellite products overestimate low rainfall events, leading to overestimation of the number of rainy days in a season. This may be the result of the sensors' much larger spatial scales than the point locations of rain gauges, as low rainfall is likely to be more patchy than heavier rainfall. Additionally, comparing point based measurements with large area pixel values would lead to a positive bias for variables with high spatial variability like rainfall in West Africa which occurs by local convective clouds (Fensholt et al., 2006). Thus for both these reasons, events with low rainfall of 1-10 and 10-20 mm are overestimated by satellite products. Although this overestimation appears to be a serious deficiency, which could lead to non-detection of drought spells during the growing season, with consequences for crop yield prediction, all satellite products have the opposite tendency for high rainfall events, which they underestimate. Thus for dekadal, monthly

540 and seasonal rainfall the overall tendency is slight underestimation, and the overall estimates of
541 rainfall amounts are good.

542 For estimating temporal trends for rainfall variables averaged over stations in northern Nigeria,
543 our gauge data indicate recovery of rainfall since the drought decades of 1970s and 80s. This
544 recovery, observed from both gauge and CHIRPS data between 1981 and 2015 appears to be due
545 to increases of about 2 mm a year in the later part of the rainy season from August to October, with
546 these months now contributing over 50% of annual rainfall. Thus both data types observed stronger
547 rainfall recovery in the months of August and September, and CHIRPS data suggest particularly
548 strong recovery in the northeastern states. Since sorghum enters a high water use period in the late
549 growing season in August, this reduces the risk of late drought impeding the swelling of grain
550 which affects dry weight production.

551 Furthermore, our observed significant positive trends for number of days of heavy rainfall over 30
552 mm, and for consecutive wet days, but insignificant trends for dry spells suggests that this recent
553 rainfall recovery may be related to increase in number of rainy days, a higher number of extreme
554 rainfall events and later cessation of rainy season, rather than a reduction in the length or number
555 of dry spells. The onset of rainy season shows small negative (earlier start), but non-significant
556 trends in most parts of northern Nigeria, so indicating little change in the start of the rainy season.
557 Thus longer rainy season in recent years, appears to be due to a later cessation of rains.

558 Conversely to gauge data averaged over the whole of northern Nigeria, which indicate a slight but
559 non-significant increase in the number and average length of dry spells, CHIRPS data indicate a
560 significant and decreasing trend in dry spells in some areas. These are in northwestern Nigeria
561 around the city of Sokoto and in the southern part of the study areas around the cities of Jos and

Abuja. This would have favourable outcomes for crop production and crop security, as a non-interrupted supply of moisture throughout the growing season is essential for a good yield.

CHIRPS-based rainfall variables indicate spatial differences in the observed large increases in seasonal rainfall over the last 35 years. The increase is especially marked in northeastern and north central Nigeria around the cities of Maiduguri and Kano, both of which have dense rural populations dependent on agricultural produce for their livelihoods. The patchy nature of rainfall variables across northern Nigeria affirms the need for the spatial perspective offered by satellite observations.

6. Conclusion

The only previous satellite-based studies of rainfall trends in West Africa (Sanogo et al, 2015; Zhang et al, 2017) were at continental scale, and used ARC satellite product, which is at a coarser (10 km) resolution, and is more reliant on the sparse network of ground stations across West Africa, than CHIRPS. The ARC products were found to be consistently inferior to CHIRPS, when compared to data from 18 rain gauges across northern Nigeria over a 30-year period, and the study did not address regional or local implications of observed trends. The CHIRPS data at 5 km resolution rely on a wider variety of satellite data inputs, as well as ground stations. The CHIRPS data were in agreement with gauge data, observing an increase in annual rainfall over the last 35 years, whereas Sanogo et al (2015) observed a slight decrease over our study area.

The study indicates that all satellite products slightly underestimate dekadal, monthly and annual rainfall. This is due to detection of a higher number of rainy days due to recording a higher number of low rainfall events than at ground stations. Consequently they also retrieve a higher number of rainy days and fewer and shorter drought spells during the growing season, than do ground stations,

which may have serious implications for crop yield prediction and consequent perceptions of food security. However, since satellites tend to also underestimate high rainfall events, the over-and under-prediction cancel out when considered at dekadal, monthly and seasonal time scales, thus the overall prediction of rainfall amounts by satellite products is good.

For trends in seasonal rainfall variables, both gauge and satellite data show increased growing season length over the last 35 years, which is due to increases in rainfall in the later part of the rainy season. This is expected to have favourable implications for local subsistence crops, especially sorghum which has lower drought tolerance at the ripening stage. Although satellite data do not show significant correlation with gauge data for number and length of dry spells, because the data are consistent among satellite products, this is not thought to affect the detection of trends. CHIRPS data indicate a decrease in the number and length of dry spells across northern Nigeria, and especially in northwest and north central Nigeria around the cities of Sokoto, Jos and Abuja, all in the densely populated Sudan zone and northern Guinea. This reduction in dry spells is potentially favorable for crop yields, and could have played a role in the increase in rural population densities over these 35 years of the study. The currently low nutritional status combined with a return to the drought conditions of earlier decades, could therefore bring severe hardship to rural households.

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